More about the Study of Floor-plan shape Influence on Buildings' Response to Earthquakes

L.Teresa Guevara[1] and Edgar Fortoul[2]
1. V&G Arquitectos, Caracas, Venezuela
2. Inmicro, Inc., Caracas, Venezuela

Abstract

Irregularities in the geometry of floor-plan configurations are identified by the "reentrant corner" condition such as those we find in buildings with "+", "H", "T", "L", "U", or "L" floor-plan shapes. The shape of a floor plan responds mainly to architectural decisions related to function, spatial relationships and other concerns. However, these decisions determine the characteristics and locations of structural and non-structural elements and establish other characteristics of a building that are significant in relation to its earthquake resistance.

The different wings generated by the irregular floor plan will have different dynamic behaviour because of their particular geometric and dynamic characteristics and position relative to the direction of the ground motion. The study of buildings that have been significantly damaged in earthquakes has shown that this condition determines an irregular distribution of the lateral force resisting elements producing considerable torsional effects and concentration of stress at the vertice of the reentrant corner. Although building damage cannot entirely be attributed to floor-plan irregularities, this aspect has been acknowledged as one important factor on the response of buildings to earthquake effects. According to post-earthquake reports and empirical research, buildings with irregular floor plans appear to be more susceptible to larger deformations and damage when subjected to earthquake motions than those with regular floor plans.

This paper presents the latest results of the systematic study of the influence of floor-plan shape on the earthquake resistant behaviour of buildings initiated by Guevara (1989). The main objective of the general research is to provide guidelines for building designers, engineers and architects, to be applied when making initial decisions in the design and analysis of buildings with irregular floor-plans in earthquake prone zones. A multidisciplinary team is working on the main research. Some recommendations, based on empirical research and in data provided by other authors, are included in Guevara (1989 , 1992).

This paper presents the results of applying different dynamic analysis methods to the study of the influence of floor-plan irregularities in the earthquake-resistant behaviour of buildings. A computer program, SET (Structural Engineering Tool) 2D and 3D, is used. At the end, numerical examples of model's application are illustrated.

Introduction

Earthquake resistance is only one of many important issues that architects must consider in the design of the total building, and these professionals have often relied on the structural engineer to satisfy the structural engineering requirements included in building codes, while dedicating more time to the development of functional and aesthetic aspects. However, observation of buildings that have been significantly damaged by earthquake effects has shown that architectural decisions related to aesthetics, function, cost, circulation, spatial relationships and other concerns affect the shape, dimensions, and location of structural and non-structural elements, determine the existence and/or location of appropriate force-resisting walls and cores, and establish other characteristics of a building that are significant in relation to its earthquake resistance.

An important factor is floor-plan shape. Buildings with irregular floor-plan shapes have been observed to be susceptible to significantly larger deformations and damage when subjected to earthquake motion than buildings with regular shapes. It is important to remark that although the torsional effects produced on a building by an earthquake will depend not only on floor-plan shape, this aspect has been acknowledged as one of the main reasons for producing these effects on buildings. Irregular distribution of the lateral force resisting elements in a building produces as an unbalanced condition in the building's mass and stiffness which, in turn, produces plan rotation or torsion. These torsional effects are difficult to assess properly and can be very destructive when overlooked.

In most of the worldwide official lateral force requirements, the use of irregular floor plans is discouraged, although they are widely used and will continue being used for housing, schools and hospitals, since they provide a greater percentage of perimeter rooms with access to natural lighting and ventilation.

Accurate evaluation of the effects that irregularities in floor-plan configuration can produce in the overall response of a building to an earthquake is very important in the assessment of potential damage. This has to be considered by both the architect and the structural engineer in the early phases of the design process when relevant decisions on floor-plan geometry are made.

This paper presents the latest results of the systematic study on the influence of floor-plan shape on the earthquake resistant behaviour of buildings initiated by Guevara (1989). Some recommendations, based on empirical research and in data provided by other authors, were included in Guevara (1989, 1992).

In Guevara et al. (1992), hypothetical structures with H-shape and L-shape floor plans were analyzed. The study of these models was undertaken by analyzing, for each floor plan shape (H and L), first, a regular rectangular floor plan with determined proportion (initial models); and, second, these floor plan shapes were transformed into irregular H- and L-shape floor plans, respectively, by taking chunks of different dimensions from them. The main reason for analyzing H-shape and L-shape floor plans was to corroborate, through a dynamic analysis, the hypothesis that buildings with these types of floor-plan shapes behave inadequately under the action of seismic forces. The building models were idealized by a system of independent frame elements interconnected by floor diaphragms which are rigid in their own plane. The displacement stiffness method, which takes into account the rotation and horizontal displacements of floors and modal superposition technique using site dependent spectral shapes, was used to calibrate the assumptions of the simplified model. The results obtained from the dynamic analyses were: the variations on the respective buildings' periods were negligible; in all the case-studies, the location of the centre of rigidity and the centre of mass coincided. Therefore, no eccentricity was identified. The conclusion is that structural response analysis used in the study which considers the already described assumptions led to inaccurate results , i.e. the results obtained from the structural response analysis did not reflect the expected behaviour of the H-shape models which was anticipated based on empirical research. From observations of significantly damaged buildings in recent worldwide earthquakes, H-shape floor plans have been found to induce deformations and torsions in buildings subject to ground motions. It is important to mention that the analysis method as well as the assumptions used in this study are used worldwide by 90% of the available dynamic analysis programs. As a consequence, we concluded that the assumption of infinite rigidity of diaphragms in their own plane did not reveal what occurs in actual cases. It was recommended that the H-shape models be analyzed with a structural response analysis which includes the flexible diaphragm assumption.

In Guevara and Fortoul (1993), the most important characteristics of structural response analysis, according to the compatibility degree between the different elements of the structural system, were studied in order to evaluate the results. It was assumed that diaphragms are, as usual, transversely infinitely rigid, and regarding rigidity in their own plane, two different models were studied: Infinitely rigid diaphragms (RDM) and flexible diaphragms (FDM).

An introduction into the main topic of the general research, irregular floor-plan shapes, and the latest findings, the results of the evaluation of different dynamic analysis methods applied to the study of the influence of floor-plan irregularities in the earthquake-resistant behaviour of buildings, are presented in this paper. A computer program, SET - Building (Structural Engineering Tool) 2D and 3D, is used. At the end, numerical examples of the model's application are illustrated.

Floor-plan Variables

The following paragraphs describe the main geometric variables that have been studied for the identification of "irregular" floor plans as part of the basis of the main research. This research is restricted to buildings with "irregular rectangulate" floor-plan shapes in reinforced concrete frame structures. The term "rectangulate" identifies shapes characterized by polygons with re-entrant corners whose sides meet orthogonally. For example, those illustrated in Figure 1.

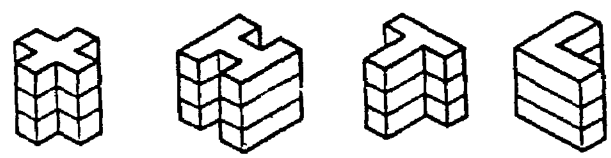

Figure 1: Irregular Rectangulate Floor-Plan Shapes

In this study, the main variables that define the characteristics of floor plans are: "Symmetry", "Proportion", and "Reentrant Corners". However, even when buildings have floor-plan shapes which belong to the same family (for example, all those in the "H-shape" family), they do not necessarily possess the same degree of vulnerability to earthquakes. The vulnerability will depend on:

(i) proportions of the rectangular components of the floor-plan shape,

(ii) the location within the figure of reentrant corners,

(iii) the number of axes of symmetry, and

(iv) the displacement of the centre of rigidity in relation to the centre of mass (torsional eccentricity).

Symmetry: This in geometric terms is a very important property when describing and identifying the characteristics of irregular floor plans. However, in terms of earthquake resistance, it is important to point out that though the geometric form determines the configuration of the building system, what is really important is structural symmetry which does not necessarily correspond to geometric symmetry in a floor plan. Structural symmetry is determined by the mass, dimension and dynamic properties of structural components and by the way these components are distributed in the floor plan. Structural asymmetry leads to torsional eccentricity and hence to torsional effects which are induced when the centre of rigidity does not coincide with the centre of mass. The building then rotates about its centre of rigidity instead of about its centre of mass. When this rotation occurs, the weakest elements fail and the building might collapse. The more eccentricity (distance between the centre of rigidity and the centre of mass), the greater the twisting or torsional effect on the building and, hence, the greater the damage. However, symmetry alone is not sufficient to provide a satisfactory earthquake-resistant floor-plan proposal. Although lack of symmetry has been found to be one of the main causes of torsional effects due to earthquake forces, the other two factors, proportion and reentrant corners, are also very relevant to the response of buildings.

Proportion in Plan: This is a geometric property associated with the length-to-depth ratio of the building. In earthquake-resistant design this property is not only related to the dimensions of a rectangular floor plan but in the case of irregular rectangulate shapes to the ratio of length to depth in each of the wings. Long wings might induce serious diaphragm deformations which might lead to torsional effects.

Reentrant Corners: This condition leads to the identification of floor-plans as irregular, or non-convex, polygons. In irregular floor-plan shapes, such as "+", "H", "T", "L", "U" or "L", the structure is formed by different wings. The dimension of the offset and the proportion of the derived wings will determine the vulnerability of the building. Each wing will react to the displacements and the torsional effects produced by ground motions in a different way. Under the action of earthquake forces, each wing will have a different dynamic behaviour because of its particular stiffness and position relative to the direction of horizontal forces. The movement of the different parts of the building can be very complicated, producing considerable diaphragm deformation, torsional effects and concentration of stress at the vertices of reentrant corners.

Although there are other important factors that influence the response of buildings to earthquake forces, such as the mass of the building, the materials used, the structural system, and variations in the elevation geometry, the floor-plan shape affects the distribution of the torsional effects in a significant way. When a poor choice of geometric parameters for a floor-plan shape (reentrant corners, proportion, symmetry) is combined with other inadequate earthquake-resistant design features, the vulnerability of the building could be increased and the total effect could be disastrous.

According to post-earthquake reports and empirical research, buildings with irregular floor plans appear to be more susceptible to larger deformation and damage when subjected to earthquake motions than those with regular floor plans.

Description of the Structural Models

The analysis of a two-storey structure's response to earthquakes presented in this paper considers, as usual, building models which are idealized by floor diaphragms which are transversely infinitely flexible and vertical elements (bearing walls, columns, bracings, etc.) which might be joined, at the diaphragm level, by horizontal elements (beams, girders, etc.). It is also assumed that all the components are solid web elements, that is, in their transversel section, the centre of gravity and the centre of torsion approximately coincide. The computer program used, "Set-Building" (Inmicro, 1991), is based on the analysis of frame and shear wall buildings subjected to both static and earthquake load. The static loads were combined with a lateral earthquake input specified as an acceleration spectrum response for each building model and then three-dimensional mode shapes and frequencies were evaluated.

Two different types of structural models are analyzed: those with the assumption of floors which are infinitely rigid in their own plane; we call this model "Rigid Diaphragm Model" RDM; and those with the assumption of floors which are finitely rigid in their own plane; we call this model "Flexible Diaphragm Model" FDM. In Guevara and Fortoul (1993), a detailed description of these models is included.

The following is a brief description of these models that which were applied to a two-storey structure.

Rigid Diaphragm Model - RDM: According to the degree of compatibility in the structural member connections, two different types of models were considered:

a) The RDM1 Model: The structure is idealized by a system of plane vertical substructures, frames and/or walls, connected only by floor diaphragms; it means that compatibility is limited to the corresponding horizontal translations of substructures and diaphragms, conforming to the subsystem of the structure's joints.

b) The RDM2 Model: In this case the assumption is that there is total compatibility, in which the subsystem of the structure's joints is formed by the diaphragms and the members' joints which are located on the same plane as the diaphragms.

Flexible Diaphragm Model - FDM: In this model, it is assumed that floor diaphrams are transversely infinitely flexible and finitely rigid in their own plane. Floor diaphragms are constituted by two-dimensional elements. Their behaviour is described according to the Method of Finite Elements applied to four node compatible elements and assuming the problem as a plane stress in a linear elastic medium.

According to the degree of compatibility in the column-girder joints, two different types of flexible diaphragm models have been considered:

a) The FDM1 Model: The structure is idealized by a system of plane horizontal finite elements and plane vertical substructures, frames and/or walls, connected only at the diaphragm joints; it means that compatibility is limited to the corresponding horizontal translations of the finite elements and the substructures.

b) The FDM2 Model: In this case the assumption is that there is total compatibility.

In this paper, only the FDM1 model results are presented because of space limitations.

Determination of the Maximum Seismic Response

The structural response to seismic forces is obtained by applying the Modal Method. The modal combination criterion used in these examples is the one contained in the Venezuelan Earthquake-Resistant Building Code, Norma Venezolana para Edificaciones Antisísmicas (Comisión Venezolana de Normas Industriales, 1982).

Numerical Examples on Model Applications

In order to numerically illustrate the application of each of the studied models, RDM1, RDM2 and FDM1, a two-storey H-shape floor plan structure (Figure 2) was analyzed using SET programs (Inmicro, 1991). For the different analyzed models, additional assumptions were made: a) the dimensions of the structural components are constant at all the floor levels and for all the analyzed models: (i) girders, 30 cm x 40 cm rectangular transverse section; (ii) columns, 40 cm diameter circular section; (iii) bracing members, 30 cm x 30 cm square section; and, (iv) slab, 13 cm depth. The storey height in all the floors is constant = 3 m, and the columns' span is 6 m in the x direction and 8 m in the y direction; mass is constant and uniformly distributed in the diaphragm. Regarding material characteristics, the following values were used: Longitudinal Elasticity Module, 2354 kN/cm^2; Poisson Relation, 0.20, and total weight per floor, 6590 kN (9.81 kN/m^2). The Spectral Design is defined in the Venezuelan Earthquake-Resistant Building Code (Comisión Venezolana de Normas Industriales, 1982) for Seismic Zone 4, Building Group B., Design Level ND 3, Structural Type I and, Soil Profile S2.

Some of the results of the analyses of Models RDM2 and FDM1 are illustrated in Figures 3, 4, 5, and 6 and in Tables 1 and 2. Great differences between the results of RDM 2 and FDM1 were not expected due to the height of the structure. Additionally, the analysis was repeated for the RDM1 and the FDM1 models, labelled RDM1a and FDM1a, assuming that for diaphragm's joints at the edges of the members, there exist infinitely rigid segments (length = 30 cm for girders and columns, and 28.3 cm for bracing members. Results of the FDM1a analysis are illustrated in Figure 7 and results for RDM1a and FDM1a are listed in Tables 3 and 4.

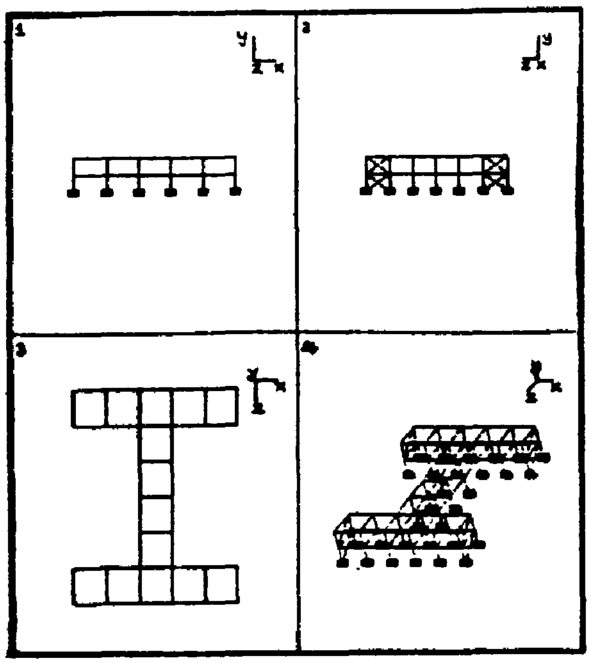

Figure 2: Analysed Two-Storey Structure

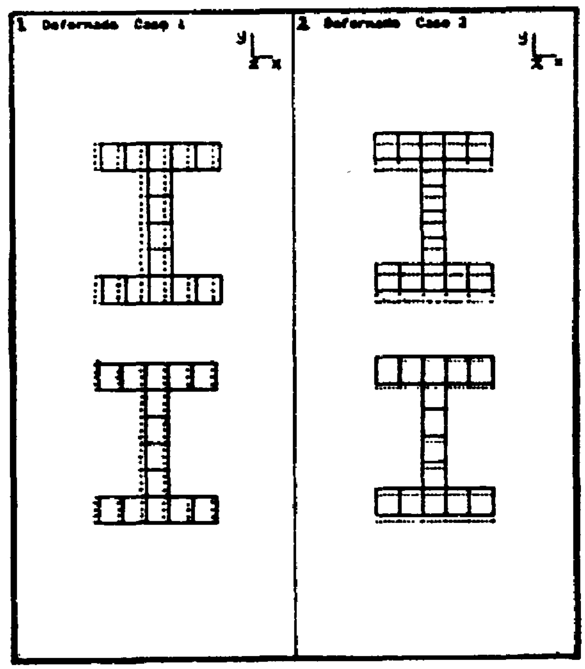

Figure 3: RDM2 Model. Modal Shapes Program SET-2D. Cases 1 and 2 = Vibration Mode.

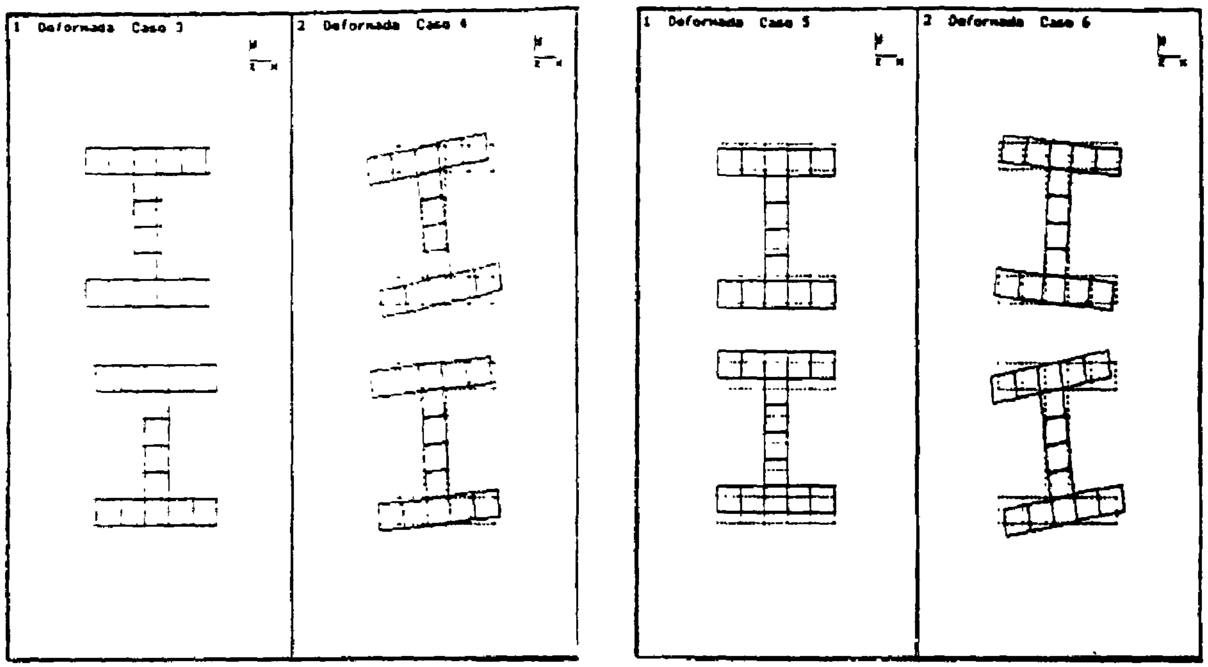

Figure 4: **RDM2 Model.** Modal Shapes Program SET-2D. Cases 3,4,5 and 6 = Vibration Mode.

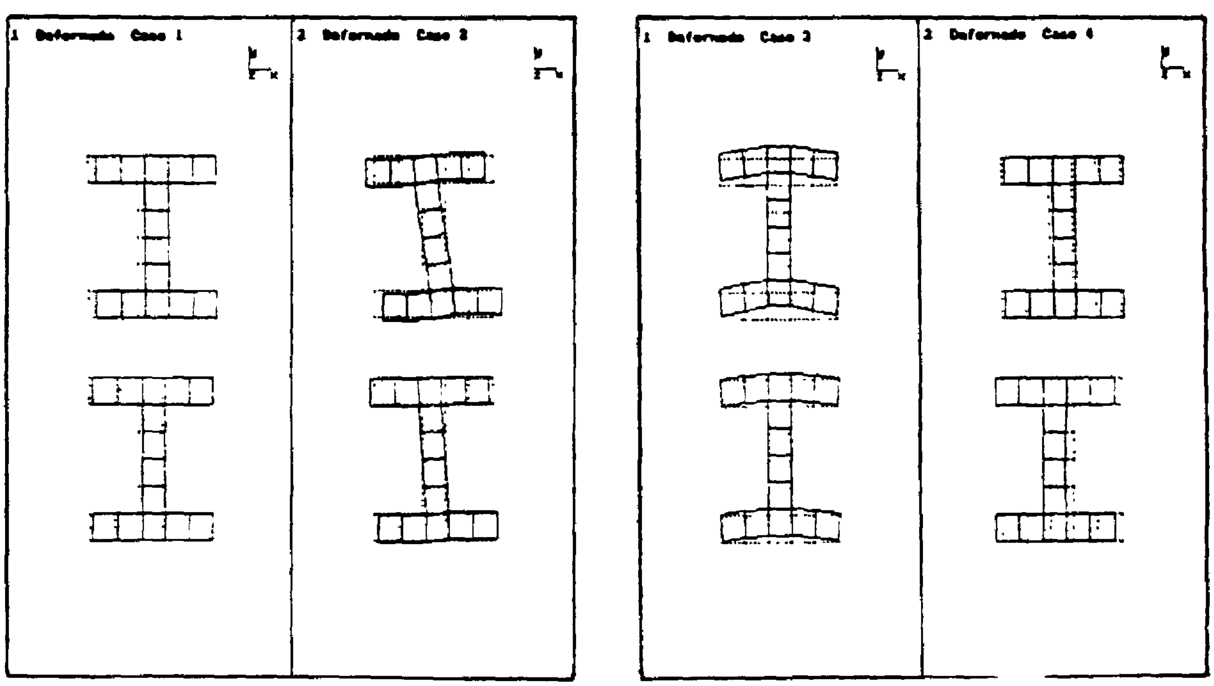

Figure 5: **FDM1 Model.** Modal Shapes Program SET-2D. Cases 1, 2, 3 and 4 = Vibration Mode.

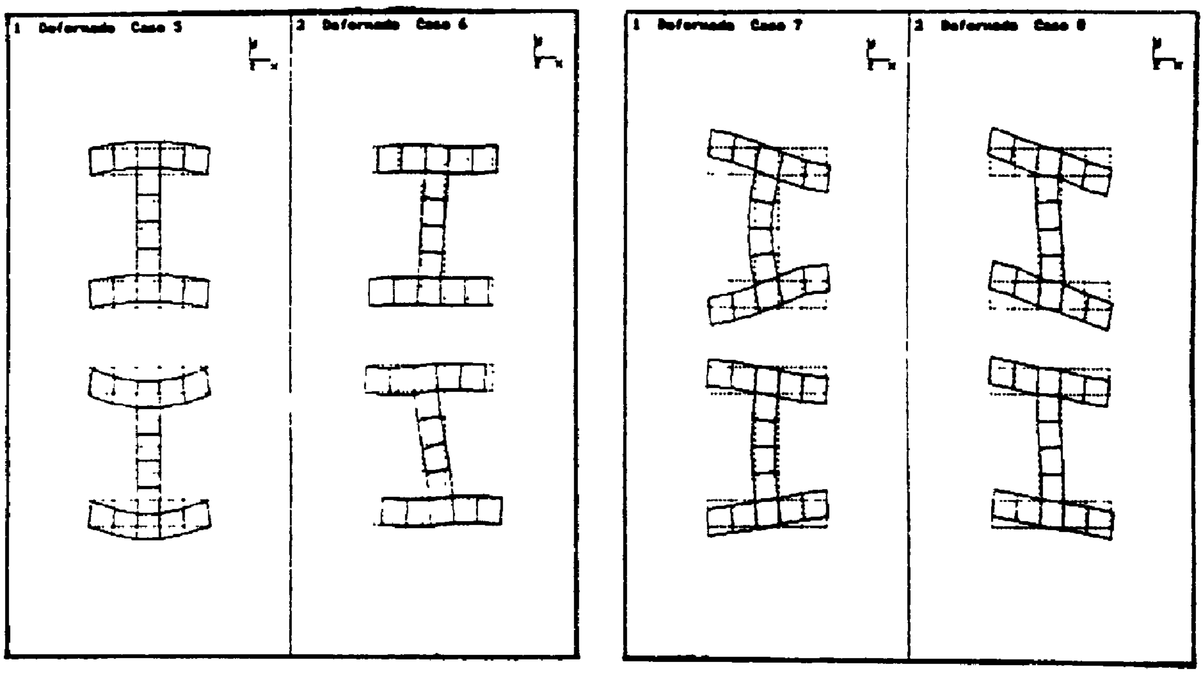

Figure 6: **FDM1 Model.** Modal Shapes Program SET-2D. Cases 5, 6, 7 and 8 = Vibration Mode.

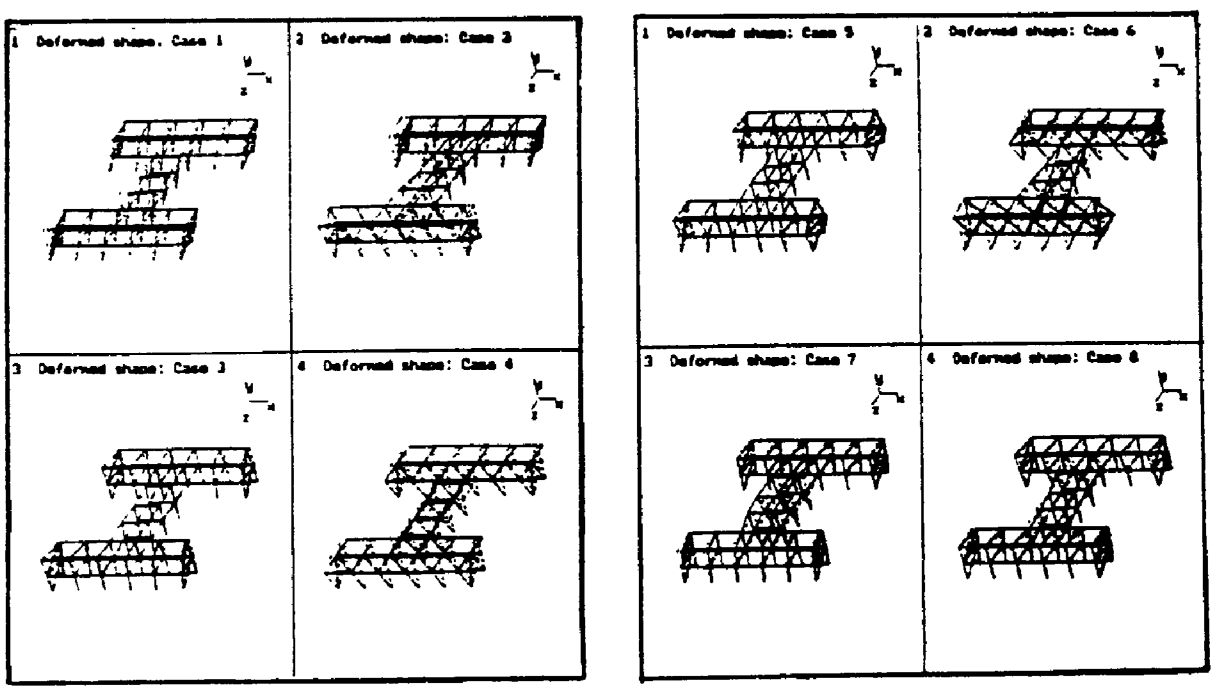

Figure 7: **FDM1a Model.** Modal Shapes Program SET-3D. Cases 1, 2, 3, 4, 5, 6, 7 and 8 = Vibration Mode.

	T (sec.)			Gx			Gy		
Mode	RDM1	RDM2	FDM1	RDM1	RDM2	FDM1	RDM1	RDM2	FDM1
1	0,6327	0,6311	0,6329	0,94047	0,94017	0,94045	0	0	0
2	0,1969	0,1968	0,2961	0	0	0	0,95514	0,95516	0
3	0,1867	0,1858	0,2954	0,33987	0,3407	0	0	0	0,90643
4	0,1693	0,1692	0,1869	0	0	-0,33989	0	0	0
5	0,0692	0,0692	0,1615	0	0	0	0,29615	0,29608	-0,29248
6	0,0596	0,0595	0,1575	0	0	0	0	0	0

Table 1 Models RDM1, RDM2 and FDM1:
Values of Period T, Participation factors Gx for EQs in the X Direction and Participation Factors Gy for EQs in the Y Direction

	EQ in X direction X(Vy=0)			EQ in Y direction (Vx=0)		
Floor Level	Vx(kN)			Vy(kN)		
	RDM1	RDM2	FDM1	RDM1	RDM2	FDM1
1	852,7	854,3	852,6	883,2	883,2	807,4
2	1248,2	1249,8	1248,1	1334,4	1334,4	1210,3

Table 2 Models RDM1, RDM2 and FDM1:
Values of Story Shear Forces Vx, Vy, in the X , Y Directions (Maximum Probable Values)

	T (sec.)		Gx		Gy	
Mode	RDM1a	FDM1a	RDM1a	FDM1a	RDM1a	FDM1a
1	0,5897	0,5899	0,94047	0,947	0	0
2	0,1901	0,2885	0	0	0,95791	0
3	0,1657	0,2865	0,32117	0	0	0,911
4	0,1637	0,166	0	-0,3212	0	0
5	0,0659	0,1474	0	0	0,28708	-0,27363
6	0,0569	0,1435	0	0	0	0

Table 3 Models RDM1a and FDM1a
Values of Period T, Participation factors Gx for EQs in the X Direction and Participation Factors Gy for EQs in the Y Direction

	EQ in X direction X(Vy=0)			EQ in Y direction (Vx=0)		
Floor Level	Vx(kN)			Vy(kN)		
	RDM1a		FDM1a	RDM1a		FDM1a
1	881,5		881,6	881,6		796,9
2	1310,1		1312,4	1341,4		1210,8

Table 4 Models RDM1a and FDM1b
Values of Story Shear Forces Vx, Vy, in the X , Y Directions (Maximum Probable Values)

Conclusions

1) Numerical differences were identified between the values obtained from the RDM's and the FDM's. However, since the modelled structure was so simple, great differences were not expected.

2) In the mode shapes of vibration, differences between the values obtained from the RDM's and the FDM's were also identified.

3) In order to illustrate in this paper the different available Structural Response Analyses for the evaluation of the influence of floor-plan irreglarities in the earthquake-resistance of buildings, a very simple structure was modelled. A two-storey structure, with an H-shape floor plan, was analyzed. However, in future research, taller buildings with H-shape floor plans are to be analyzed in order to evaluate differences in the application of Rigid Diaphragm Models (FDM's) and Flexible Diaphragm Models (FDM's).

References

Comisión Venezolana de Normas Industriales (1982). Norma Venezolana para Edificaciones Antisísmicas. COVENIN 1756-82. Ministerio de Foment, Carcacas, Venezuela.

Fortoul, P.C. (1989). Notes on the structural Dynamics Course. Decanato de Postgrado, Universidad Simón Bolívar, Caracas, Venezuela. (unpublished).

Guevara, L.T. (1989). Architectural considerations in the design of earthquake resistant buildings: Influence of floor-plan shape on the response of medium-rise housing to earthquake. Ph.D. Dissertation, University of California, Berkeley, USA.

Guevara, L.T. (1992). La Influencia de la forma de la planta en el comportamiento sismo-resistente de las edificaciones de concreto de mediana altura. Simposio Arquitectura Concreto y Trópico: Facultades y Escuelas de Arquitectura de UCV, LUZ y ULA/AVPC/SIDETUR. Caracas, Venezuela.

Guevara, L.T. , Alonso, J.L. and Fortoul, E. (1992). Floor-plan shape influence on the response to earthquakes. In: Balkema (ed.). Proceedings of the 10WCEE, Madrid, Spain, pp. 3945-3950.

Guevara, L.T. and Fortoul, E. (1993). Descripción de los modelos matemáticos utilizados para estudiar la influencia de la forma de la planta en la respuesta de las edificaciones de altura media ante terremotos. VIII Seminario Latinoamericano de Ingeniería Sismo-Resistente, Mérida, Venezuela, pp. d25 -d39.